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AN UNDERGROUND ELECTROMAGNETIC SOUNDER EXPERIMENT†

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An electromagnetic sounder developed for an archaeological application in Egypt has been successfully tested in a California dolomite mine. Chambers in the mine 100 to 130 ft from the surface gave intense, well-defined echoes consistent with an average attenuation coefficient of 0.6 db/m and a relative dielectric constant of 11. By moving the transmitter and receiver units on the hillside above the underground chambers, various characteristics of the propagation could be observed such as dispersion, chamber aspect sensitivity, and cross-section. The transmitted pulse was one to one-and-a-half radio-frequency cycles long at a peak power of 0.2 Mw. Frequencies employed were 16 to 50 Mhz. The light weight, highly portable, battery-powered equipment is potentially suited to other underground sounding applications.

INTRODUCTION

The application of electromagnetic methods for underground geophysical exploration has been both extensive and diverse during the past half-century as far as very long radio waves are concerned. In a recent historical review of this subject, Keller (in Vanyan, 1967) lists over 150 references in the literature. Such references show increased recent interest in underground propagation of electromagnetic waves with application to long-distance communications beneath the surface of the earth, and to the use of short pulses for detection of buried objects, faults, and discontinuities from the surface. Surface maps of ground conductivity based on data from commercial broadcast stations show that moderate to high attenuation rates can be expected for electromagnetic signals propagated underground near the surface at many locations; however, low frequencies are successfully used for detecting strata to considerable depths. El-Said (1956) has used interference patterns from the continuous wave signals of local broadcast stations to locate the water table in the Egyptian desert 560 m below the surface sands.

Sounder studies (Waite and Schmidt, 1961) of glacial ice have been made by several groups, and dielectric properties of rocks at frequencies above one Mhz have been under much more investigation in recent years. Two successful electromagnetic sounder experiments (Simmons, 1973) were conducted on the moon during Apollo 17. Frequencies as high as 230 Mhz and 1 Ghz have been used for mapping boundaries of buried salt domes (Unterberger et al, 1973; Holser et al, 1972).

While one cannot hope to use underground EM probing successfully in every environment because of the sometimes severe propagation losses, neither can one write off the potentially great usefulness of such methods in archaeology, geology, mining, and hydrology in some environments. Archaeological sites, for example, are frequently found in desert areas where the water table is far below the surface, and the annual rainfall is very small. These very dry conditions tend to improve propagation of electromagnetic waves in the rock or sand, making these desert sites favorable for electromagnetic prospecting techniques. In such areas, it appears that there is a good chance that radio techniques can be used to locate buried chambers and tunnels (and perhaps walls, floors, and other structures) at distances ranging from a few feet below the surface to several hundred feet, under optimum conditions. The experiment described in this paper was motivated by the desire to detect underground chambers at archaeo-

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logical sites, such as the pyramids of Egypt, using electromagnetic sounder techniques.

EQUIPMENT

The transmitters used in the experiment were based on a design by Hellar and Halter (1954), and Samsel (1957). This transmitter theoretically delivers a single-cycle radio frequency oscillation to a matched load, without subsequent ringing. Figure 1 shows the output of several actual transmitters with nominal frequencies of 15, 25, 33, and 58 Mhz as measured with a resistive load. The power output of each is about 200 kw. Because the exponential ringing is eliminated to a large degree, these transmitters improve considerably the prospect for detecting scattering objects close to the sounder, and also provides good spatial resolution of echoes from more than one target.

In our experiments the transmitters were coupled to the earth using broadband "bow-tie" antennas similar in shape to those often used for UHF TV reception, made either of metal-sprayed cloth or copper screen, and lying on the ground. Similar bow ties and broadband dipoles made of rectangular conducting sheets were used for receiving.

The sounder display found most useful for our purposes, the A-scope or amplitude-versus-time oscilloscope presentation, allows real-time inspection of the field of view of the sounder and monitoring of performance at the same time.

RESULTS FROM DOLOMITE MINE EXPERIMENTS

A dolomite mine in the Inyo Mountains near Lone Pine, Calif. was selected as a site for field experiments because of the low attenuation in the rock at that site. The principal experimental objective was to detect chamber A (Figure 2) and most of the site placements were determined on this basis. Figure 3 is a photograph of the exterior showing some of the equipment locations on the hillside.

In addition to the surface sounding operation with the receiver connected to the oscilloscope by a length of coaxial cable, a broadband dipole was

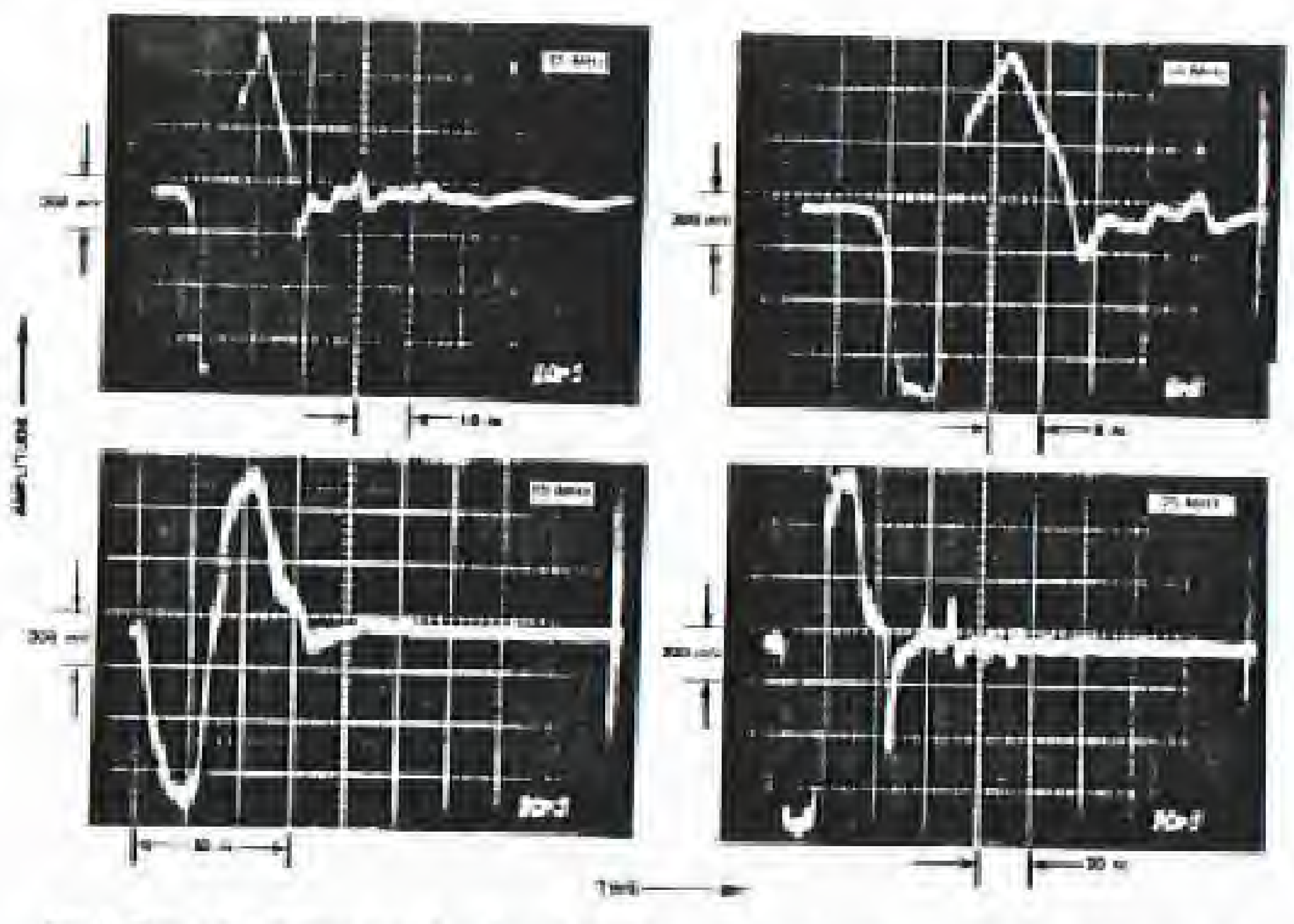

Fig. 1. Output pulses from several single-cycle impulse transmitters as measured across a resistive load.

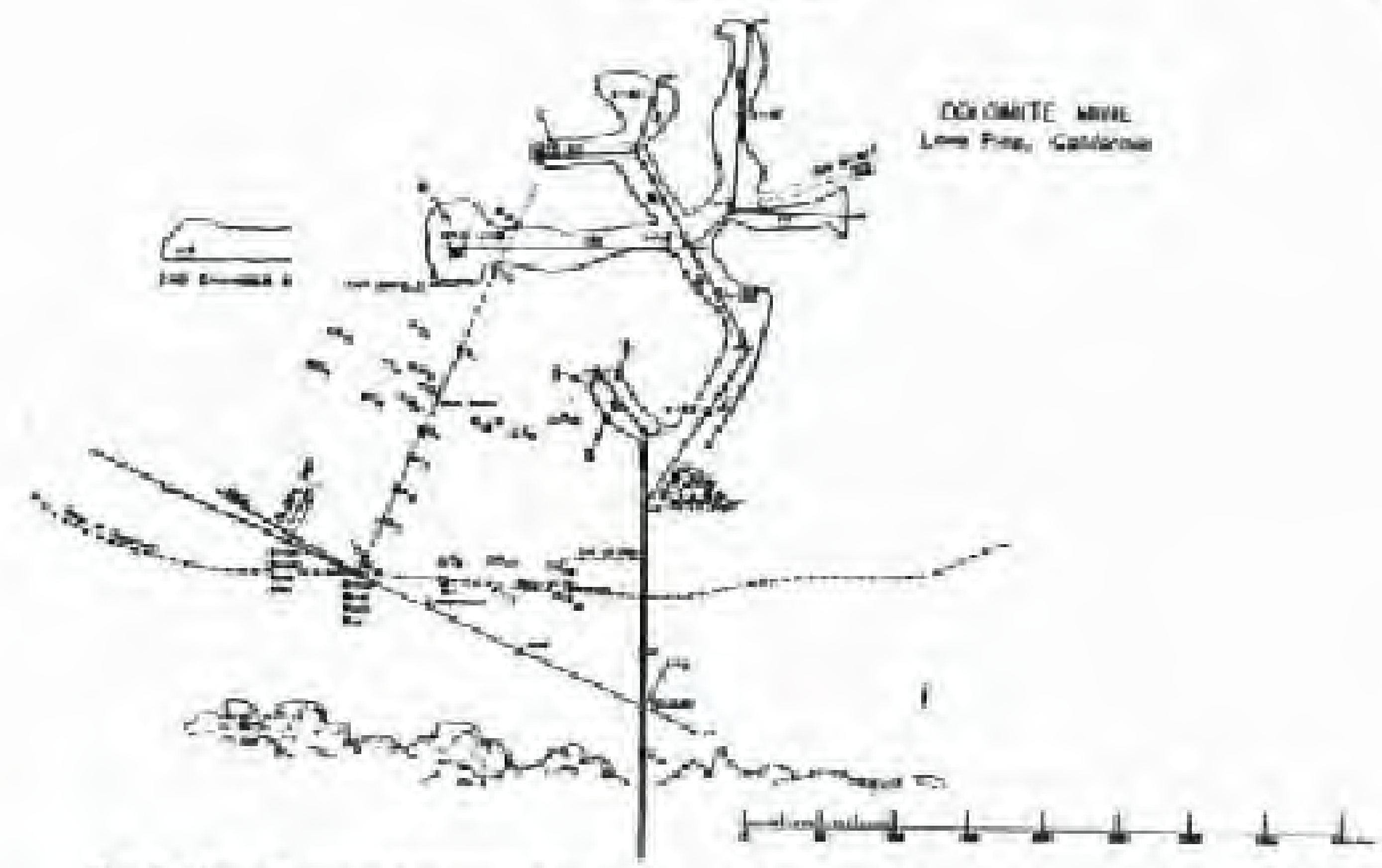

Fig. 2. Map of Premier Resources dolomite mine showing the projected locations of transmitting (T_n) and receiving (R_n) sites.

placed within the end of chamber A of the mine almost directly beneath transmitter site T_1. The signal from this dipole was also monitored at the oscilloscope outside the mine on an electrically measured length of coaxial cable, thus providing an accurate one-way propagation time from transmitter to chamber A. The method of verifying that the echoes seen were from the underground chambers was a comparison of the known geometry of the equipment at several sites with respect to the chamber, the propagation time on a one-way basis and, finally, the total two-way propagation time for the suspected echoes.

The sounder equipment external to the mine on the hillside was moved to several different sites, varying the distance to the chamber and the geometry. The equipment was finally moved to a sufficient distance and unfavorable viewing aspect that all echoes vanished.

From the known geometry of the mine it was determined that the propagation velocity of signals from transmitter into the end of chamber A was close to 0.30 c, giving an effective dielectric constant ϵ_r of approximately 11 at 25 Mhz, assuming a low loss medium.

Figure 4 shows the dielectric constant, loss tangent and attenuation coefficient of a sample of solid white dolomite[1] from this mine as measured in the laboratory. The rock in situ at the mine is faulted and broken by joints. It was not surprising, therefore, to measure a dielectric constant of 11 and attenuation coefficient of 0.6 db/m (tan δ=0.08) at 25 Mhz in the field, higher than the values of the laboratory sample, apparently because the actual mountainside consists of both fractured rock and soil. The top soil at the mine was quite wet because of recent heavy rains in the area, which should increase both the dielectric constant and conductivity of this component of the mountainside. Laboratory measurements on individual samples of solid dolomite taken from the site revealed little effect of humidity or surface moisture, indicating that groundwater in faults and joints and wet top soil were important factors in propagation through the hillside.

Figures 5, 6, and 7 present a few of the many amplitude versus time records made during the measurements in the vicinity of the dolomite

[1] Composition: 55.5 percent $CaCO_3$; 42.80 percent $MgCO_3$; 0.68 percent SiO_2; 0.20 percent Al_2O_3; 0.15 percent Fe_2O_3; specific gravity, 2.86; Mohs hardness, 4.7.

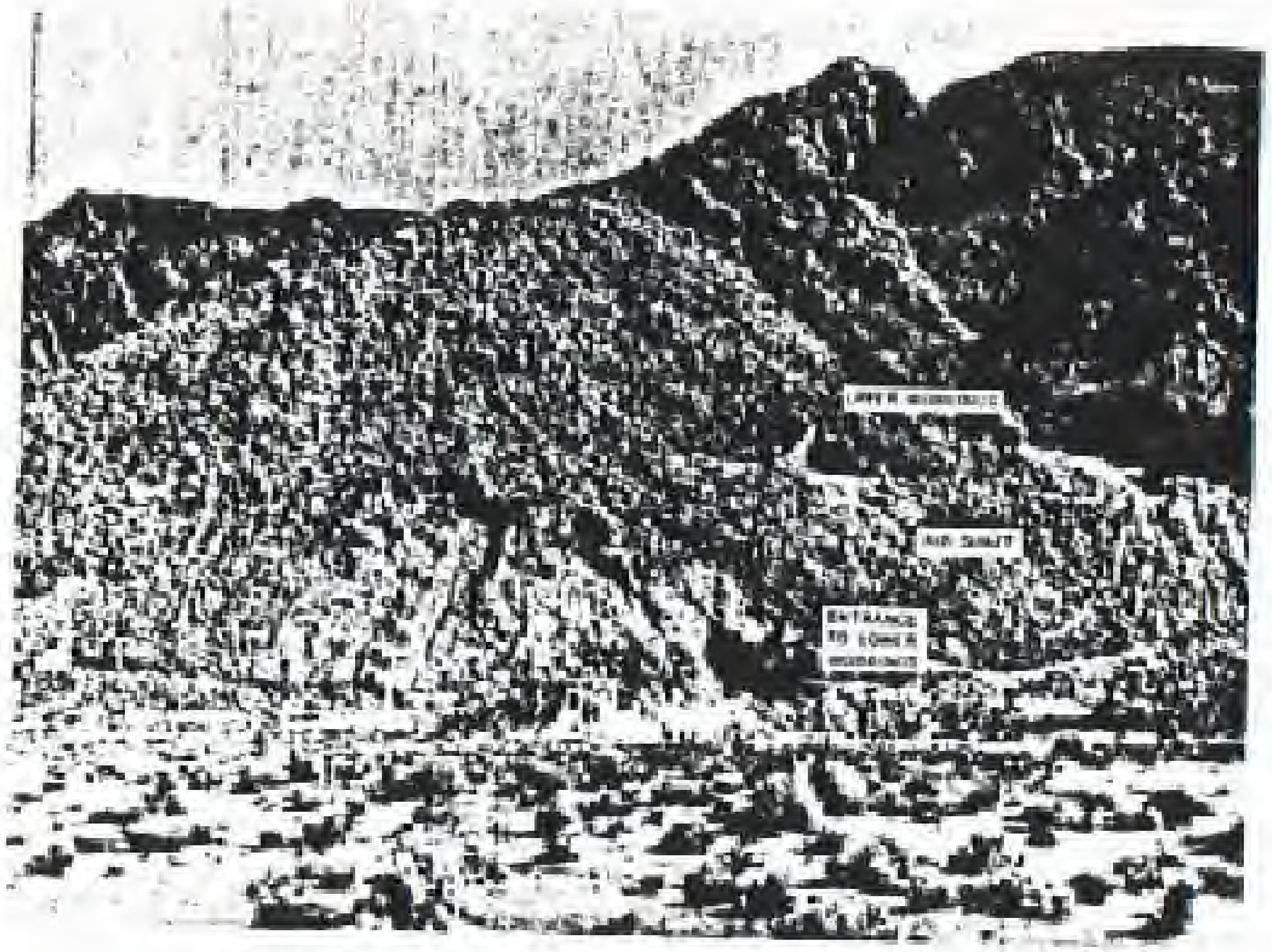

FIG. 3. Photograph of the dolomite mine site showing transmitting and receiving antenna locations on the hillside.

mine and illustrate the most important features observed in the results.

Figure 5 illustrates strong echo returns from chamber A and the result of changing the transmitter receiver geometry. It was determined from the mine survey that the geometry most closely specular with respect to the ceiling of chamber A was with the transmitter located at position T_1 and the receiver at position R_1. It was reassuring that this geometry yielded by far the largest cross-section in comparison to the many other geometries tried during the course of the experiment. For example, a comparison of Figure 5(a) and 5(b) shows a 10-db decrease in echo power by moving the receiver from position R_1 to R_2. The ceiling of chamber A had a cross-section of a little over 100 m² when spatial and absorptive losses were accounted for in the propagation equation.[1]

[1] A separate set of measurements determined the absorptive loss as 0.6 db/m, and a reflection coefficient R of 0.95. Other parameters in the propagation equation were a peak output power of 200 kw, and antenna gain factor of 3.

(A cross section of 100 m² represents an effective reflecting area of approximately 10 m² assuming a portion of the ceiling is regarded as a flat plate. The actual physical area of the ceiling was perhaps as great as 200 m².) The ceiling was quite rough, and has not been finished flat to give an ideal specular reflection, so 100 m² cross-section seems a reasonable result.

Moving the receiver from R_1 to R_2 results in a total range change of 10 ft, or difference in propagation time of 33 ns. When the 12-ns difference in triggering time between the $T_1 - R_1$ and $T_1 - R_2$ geometry is accounted for, the difference in onset time of either from the ceiling of chamber A should be 45 ns. The measured difference shown in Figure 5 is as close to agreement with this figure as can be scaled from the data.

Figure 5 also reveals that the echo duration is much greater than the transmitter pulse. One explanation is that echoes are being received from other regions of the mine. For this reason the expected onset times from what are regarded as

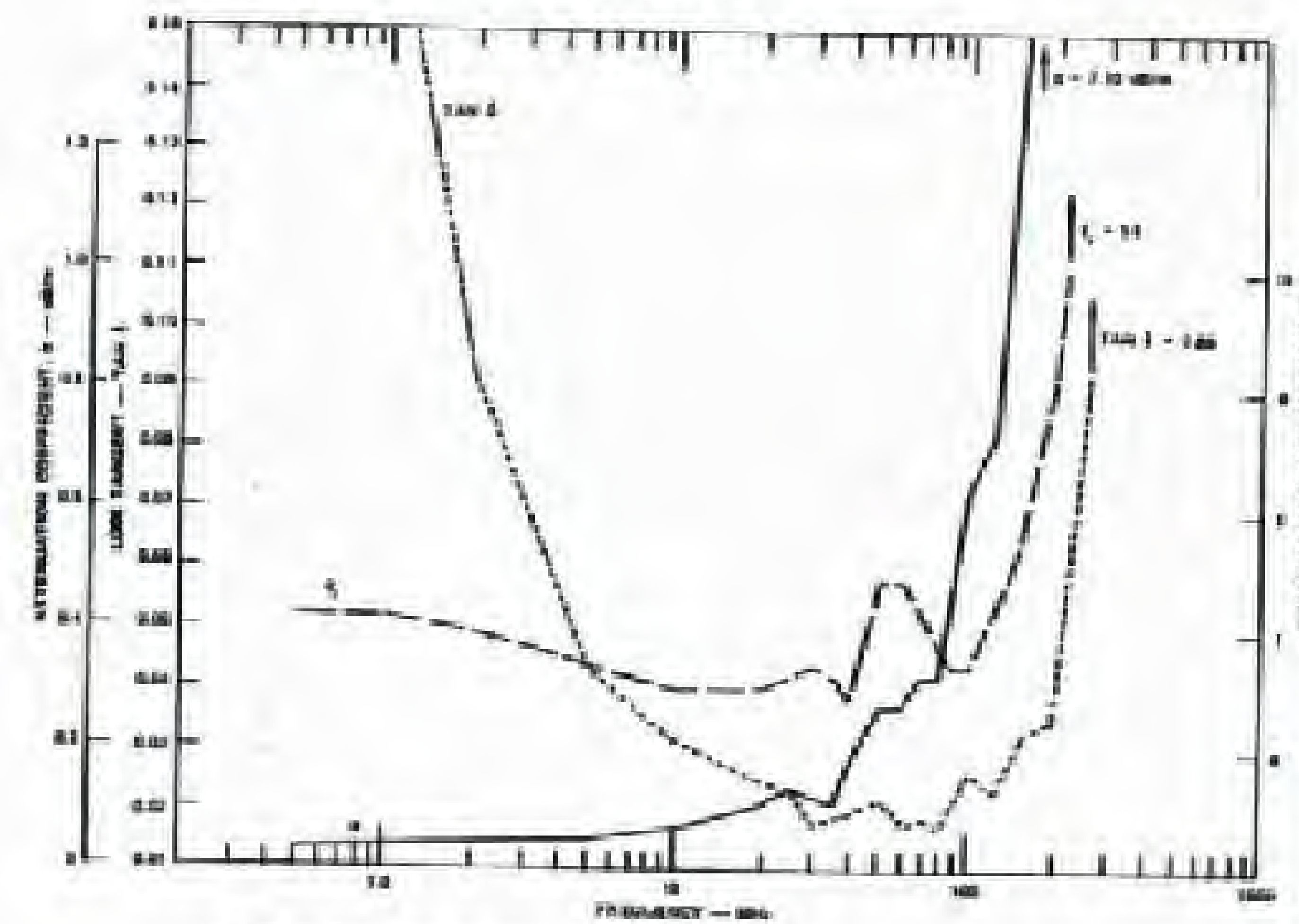

FIG. 4. Dielectric constant, loss tangent, and attenuation coefficient of a sample of dolomite measured in the laboratory.

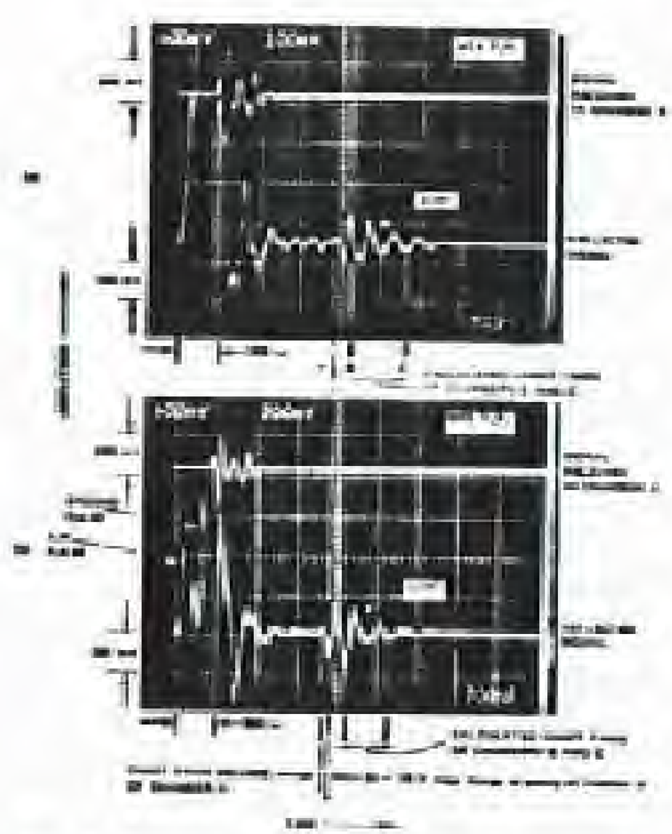

Fig. 5. Comparison showing the different ranges and amplitudes of the echoes with the transmitter (17.5 Mhz) at T_1 and receivers at R_1 and R_2.

likely reflecting areas and designated B and C (Figure 2) are shown on Figure 5. Careful examination of data in the same form as Figure 5, but from different transmitter-receiver geometries, establishes that a full explanation of the echoes requires a complicated interaction of three mechanisms operating simultaneously. The first two are dispersion of the pulse as it propagates through the medium and uniform scattering of the pulse from a rough, extended surface. The third mechanism is the reflection of the pulse from separate surfaces that slightly overlap one another in the time domain. The separation of the effects discussed above is extremely difficult.

Further detail on echoes overlapping in time is illustrated in Figure 6 which shows a time-expanded view of echoes from the $T_1 - R_1$ geometry. On the top trace, a portion of the entire oscilloscope sweep at 200 ns per division has been intensified to show the location in range of the portion shown in the bottom sweep at 50 ns per division. The calculated time delays representing the start of echoes from the roof of chamber A and a point at the end of tunnel B (point T on Figure 2)

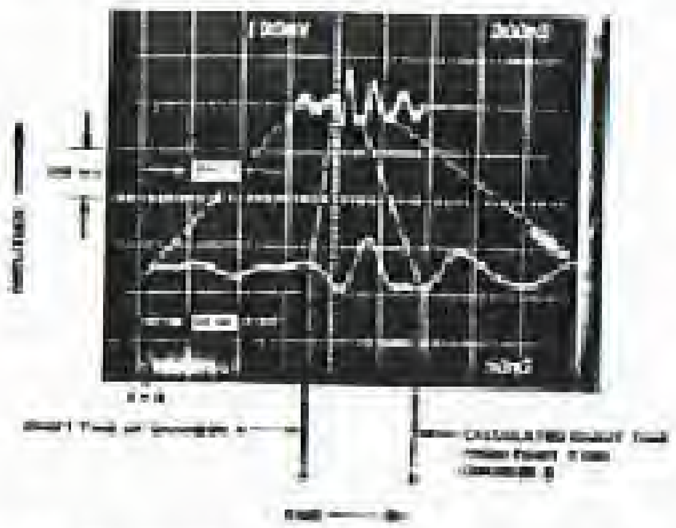

FIG. 6. Detail of the echo at T_1R_1 showing the calculated range to tunnels A and B.

are shown related to the expanded scale. Since the characteristic echo shape for a single reflection appears to have three half-cycles, it is plausible that half-cycles of opposite sense are responsible for the flat area at time B. If one accepts this argument, then a second echo begins at almost precisely the calculated time. It is necessary, in any case, to recognize that tunnel B and a site in the vicinity of J17 on the map represent favorable geometries for scattering and must be considered probable sources to partially explain the observed echo duration.

Figure 7 shows the different results obtained when different frequencies are used over the same propagating path. Figure 7 is notable for the decreasing echo strength and general change in shape or form of the echo with increasing frequency caused by dispersion of the pulse in the media.

The nominal transmitter frequencies shown in Figure 1, using resistive loads, are modified somewhat in practice by the filtering effect of the antennas used. For this reason, the 25-Mhz transmitter shown in Figure 1 appears to give a 17.5-Mhz radiated pulse, and the other transmitter frequencies are also similarly lowered.

The 17.5-Mhz transmitter—the top trace in Figure 7—gave the best overall results.

However, the advantage of the flexibility provided by several frequencies is shown in the 26 and 45-Mhz traces, in which the considerable close-in clutter of the 17.5-Mhz trace is clearly resolved into a pulse propagated through the air and a later direct pulse propagated through the ground. The transmitting and receiving antennas at T_1 and R_1 are separated by 50 ft. The direct propagation time between them through the air is then 50 ns. The time delay between the air pulse and ground pulse at 26 Mhz is 125 ns, so the total propagation time is 175 ns. This propagation time corresponds to a refractive index of 3.5 for the 50-ft ground path, in good agreement with other measures of the bulk refractive index at the site.

Several prominent hillsides and other large objects near the site should have been ideal scatterers for air-propagated echoes at ranges somewhat larger than the echoes from the mine tunnels. A search for such echoes proved, surprisingly, to give negative results. Because the surface geometry at this site does not seem especially favorable for avoiding air-propagated echoes, this test gives added weight to other evidence that air propagated echo signals are not as serious a liability in these measurements as we first feared.

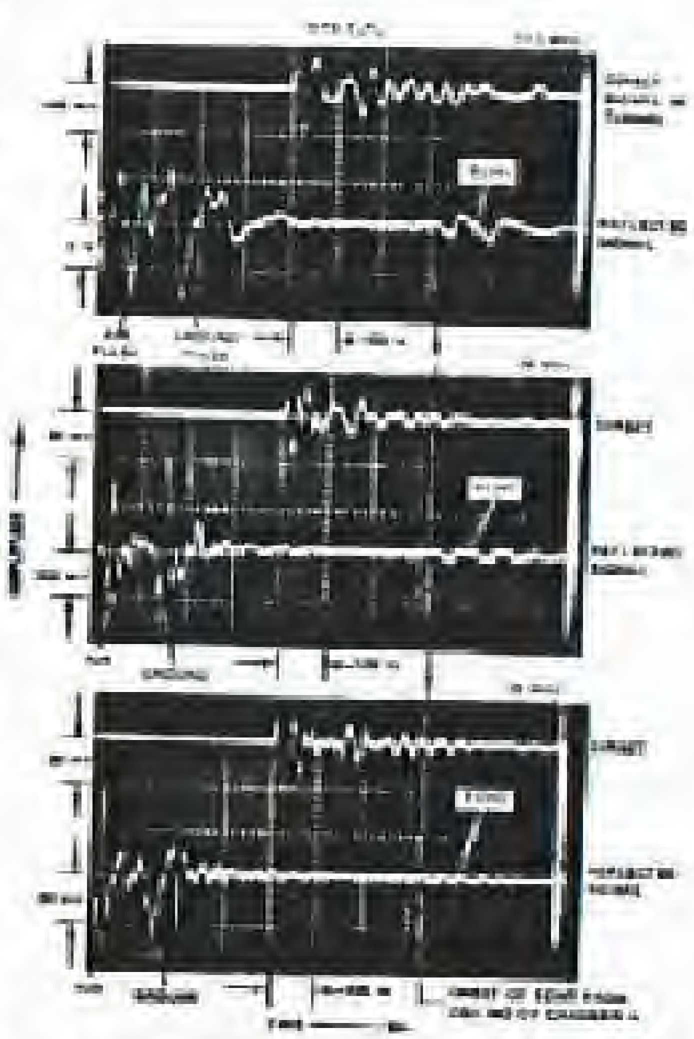

FIG. 7. Comparison of signals received using different sounder frequencies for a single pair of transmitting and receiving sites, T_1 and R_1.

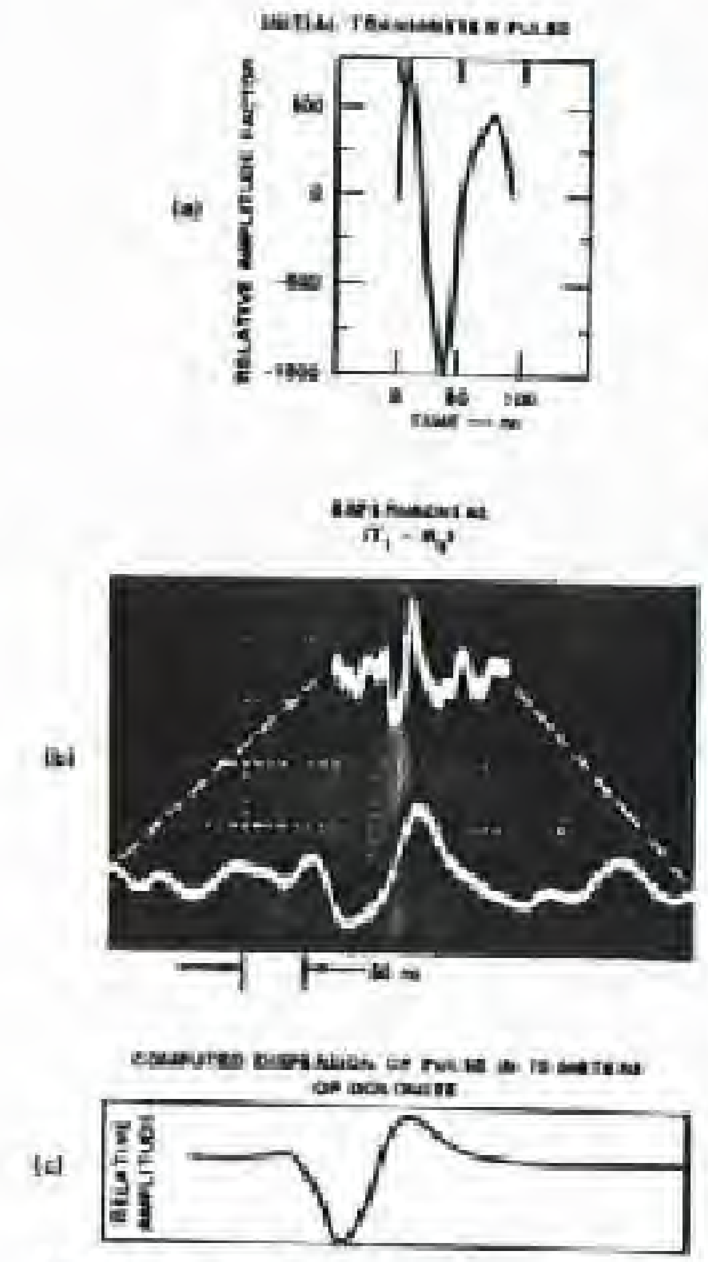

FIG. 8. Dispersion of short pulse after propagation through 70 m of dolomite.

Figure 8 (a, b, c) shows a comparison of theory and experiment regarding dispersion of the pulse as it propagates through the dolomite. Figure 8(a) represents a very close approximation to the transmitted pulse. Figure 8(b) illustrates an actual echo return for the $T_1 - R_1$ geometry where the two-way distance to chamber A is 70 m. Figure 8(c) shows a computer simulation of the transmitted pulse after propagating 70 m through dolomite, having a loss tangent of 0.1 and relative dielectric constant of 11.

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